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Alarm-condition detection and localization using Rayleigh scattering for a fiber-optic bending sensor with an unmodulated light source

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Abstract

We present a simple method for the localization of a bending loss region for a fiber-optic alarm-condition sensor based on the measurement of transmitted and Rayleigh backscattered power. Bending the sensing fiber affects both the transmitted and backscattered power of unmodulated continuous-wave (CW) light that is launched into the fiber. The position of the loss region is determined from unique relationships between normalized transmitted and backscattered powers for different locations of the disturbance along the fiber. The localization of a strong disturbance with an accuracy of 1 m at positions near the source-end and of 5 m at positions near the remote-end of a 4.04 km length single-mode fiber was demonstrated. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

One of the most important advantages of optical fiber sensors is distributed sensing that permits the measurement of a desired parameter along the test fiber [1,2]. Distributed bending-based fiber-optic sensors are very attractive for the measurement of pressure, temperature, displacement, etc., where the measurand is associated with a lateral deformation of the fiber [3–5]. The region where light loss occurs due to bending is usually localized by means of optical time-domain reflectometry (OTDR) [6] or frequency domain reflectometry, such as coherent (COFDR) [7] and incoherent optical frequency domain reflectometry (IOFDR) [8,9]. All these methods use time- or frequency-modulated light sources that allows localize a number of perturbations along the test fiber simultaneously. Meanwhile, for some applications, it is important to detect only rare but hazardous alarm conditions which typically occur

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as a single infrequent event, such as a pipe leak, fire or explosion. For such applications it is possible to use simple and inexpensive "integrating" [10] fiber-optic sensors that utilize an unmodulated light source, an intensity detector and a lengthy sensing fiber. However, these sensors provide only the measurement of the integrated value of a parameter or parameters over some spatial domain [10], but do not localize the perturbed region.

In this paper, we present a novel extended method that allows us not only to detect the alarm-condition but also to localize a single disturbance for loss fiber-optic sensors using an unmodulated continuous-wave (CW) light source.

2. Operating principle

The experimental set-up for verification of the proposed method is shown in Fig. 1. CW light emitted by a super-luminescent diode operating at a center wavelength of about 1550 nm with a linewidth of about 50 nm was launched into a 4.04 km long standard single-mode fiber through an optical circulator. The launched optical power was about 400 μW. The optical isolator was used to cancel back reflection from the output end of the sensing fiber. A standard two-channel lightwave multimeter was used to measure the transmitted and Rayleigh backscattered powers. Transmitted and backscattered powers were normalized with respect to their initial undisturbed values. To induce the bending losses in the sensing fiber, we

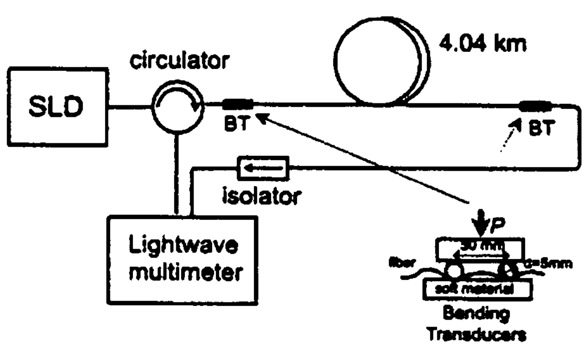

Fig. 1. Experimental set-up.

used bending transducers, which are also shown schematically in Fig. 1.

The basic idea of the proposed method is to localize the perturbation by using the unique relationships between normalized transmitted and Rayleigh backscattered powers of an unmodulated CW light source for different locations of the loss-induced disturbance along the sensing fiber. If, for example, the bending losses occur at the remote-end of the sensing fiber (see Fig. 1), an increase in the load P leads to a proportional decrease of the transmitted power. However, it does not change the Rayleigh backscattered power, because all fiber length participate in backscattering and the launched power is the same such as for undisturbed fiber. But if we bend the sensing fiber close to the source-end, the decrease in transmitted power is accompanied by a decrease in the Rayleigh backscattered power. Because in this case the launched into the fiber power is decreased and backscattered power is also decreased due to the induced losses. Further, if we bend the sensing fiber in the middle, the first half of the fiber, which is closer to the source-end scatters the light as well as half of undisturbed fiber, but the power scattered from the second half is less due to losses induced in the middle. So, in general, for the identical loss-induced perturbations the value of the decrease in normalized backscattered power depends on the location of the excess loss region.

To find an analytical expression for calculation of the distance from the fiber source-end to the location of the loss region, we will analyze the configuration with two plain fiber sections whose lengths are l_1 and l_2, respectively, and a short fiber piece between them affected by a monitored condition. Plain fiber sections possess Rayleigh scattering and attenuation due to light absorption. The power reflection coefficient of each Rayleigh scattering fiber segment can be calculated as [11,12]

$$R_{\delta L} = S(\alpha_s/2\alpha)[1 - \exp(-2\alpha\delta L)]. \quad (1)$$

where α_s is the attenuation coefficient due to Rayleigh scattering, α is the total attenuation coefficient of the test fiber, δL is the length of the fiber segment, and recapture factor S for the single-mode step index fiber is [13]

$$S = b(n_1^2 - n_2^2)/n_1^2, \tag{2}$$

where b depends on the waveguide property of the fiber and is usually in the range of 0.21–0.24 for single-mode step-index fiber [13], n_1 and n_2 are the refractive indices of the fiber core and cladding, respectively.

Introducing a parameter $S_\alpha = S(\alpha_s/2\alpha)$, the transmission and backscattering coefficients of plain fiber sections can be written as $T_{1,2} = \exp(-\alpha l_{1,2})$ and $R = S_\alpha(1 - \exp(-2\alpha l_{1,2})$, respectively. The short fiber piece is affected by a monitored condition so that it introduces light loss and has a transmission $T_S \leqslant 1$. Let us assume that the scattering is relatively weak and the portion of the scattered light is very small. This allows us to simplify the analysis, neglecting multiple scattering in both directions. The Fresnel reflections with coefficients r_1 and r_2 from the fiber source- and remote-ends, respectively, have to be taken into account, because even a weak reflection can be comparable to the back scattering. However, we can assume that $r_{1,2} \ll 1$ and neglect multiple reflections as well. In this case, the transmission T and back-scattering R coefficients of this optical system can be written as

$$T = T_1 T_S T_2 = T_S e^{-\alpha L}, \tag{3}$$

$$R = r_1 + S_\alpha(1 - e^{-2\alpha l_1}) + T_1^2 T_S^2 S_\alpha(1 - e^{-2\alpha l_2}) + T_1^2 T_S^2 T_2^2 r_2, \tag{4}$$

where $L = l_1 + l_2$ is the total sensor length. Further simplification of R yields

$$R = -S_\alpha(1 - T_S^2)e^{-2\alpha l_1} + (r_2 - S_\alpha)T_S^2 e^{-2\alpha L} + S_\alpha + r_1. \tag{5}$$

Normalized coefficients are defined as $T_{norm} = T/T_{max}$ and $R_{norm} = R/R_{max}$, where T_{max} and R_{max} can be evaluated from the above equations when $T_S = 1$. This leads to

$$T_{norm} = T_S, \tag{6}$$

$$R_{norm} = \frac{S_\alpha + r_1 - (S_\alpha - r_2)T_S^2 e^{-2\alpha L} - S_\alpha(1 - T_S^2)e^{-2\alpha l_1}}{S_\alpha + r_1 - (S_\alpha - r_2)e^{-2\alpha L}}. \tag{7}$$

The relationship between the normalized transmitted T_{norm} and Rayleigh backscattered R_{norm} powers can be found from Eqs. (6) and (7)

$$T_{norm} = (\{(S_\alpha + r_1)(R_{norm} - 1) - R_{norm}(S_\alpha - r_2)e^{-2\alpha L} + S_\alpha e^{-2\alpha l_1}\}/\{S_\alpha(e^{-2\alpha l_1} - e^{-2\alpha L}) + r_2 e^{-2\alpha L}\})^{1/2}. \tag{8}$$

This relationship is shown in Fig. 2 when bending losses occur at distances $l_{1,n} = n\Delta l$ from the source-end of the test fiber, where $n = 0, 1, \ldots, 10$, and the interval between bending locations $\Delta l = 404$ m. A typical value for $b = 1/4.55$ for single-mode fiber [14] was used in the calculations. A good agreement between experimental data and theory was obtained for $(\alpha_s/\alpha) = 0.26$, that is quite reasonable for the fiber, which was used in the experiment with total attenuation coefficient $\alpha = 0.5$ dB/km [14]. Reflections from the source-end and the remote-end of the sensing fiber, which are respectively equal to 0.15×10^{-4} and 0.27×10^{-4} in our experiment, were also taken into account in the calculations.

To localize the perturbation with the proposed method, we need to find a parametric curve that passes through the point with coordinates equal to the measured normalized Rayleigh backscattered and transmitted powers. The location of the loss region can also be found directly from Eq. (8)

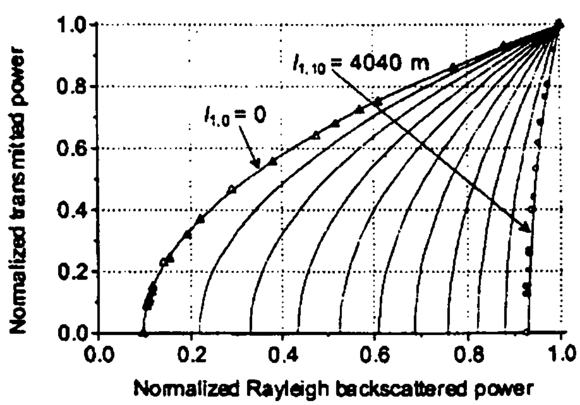

Fig. 2. Theoretical (solid lines) and experimental (points) relations between normalized transmitted and Rayleigh backscattered powers for bending losses induced close to the input (Δ), and close to the remote-end (o), of the sensing fiber, respectively.

$$
\begin{aligned}
l_1 = & -\frac{1}{2\alpha}\ln\{((1-R_{\text{norm}})(S_\alpha + r_1) \\
& -(R_{\text{norm}} - T^2_{\text{norm}})(S_\alpha - r_2)e^{-2\alpha L}) \\
& /S_\alpha(1-T^2_{\text{norm}})\}.
\end{aligned} \tag{9}
$$

Therefore, the measurement of the normalized transmission and backscattering powers, as well as the knowledge of the fiber attenuation coefficients α and α_s, provide the calculation of the distance l_1 from the fiber source-end to the fiber section with induced losses.

As is well known, excess losses induced by bending the sensing fiber depend on the amplitude of the perturbation. Therefore, the decrease in transmitted light power can be used for the measurement of the disturbance [3–5]. So, with the proposed extended method, we can provide both detection and localization of the single perturbation that induces losses in the test fiber.

3. Experimental results and discussion

Fig. 2 also presents the results of the experimental measurements of normalized transmitted and Rayleigh backscattered powers for bending losses that were induced near the input and near the remote-end of the test fiber. The small differences between measured and calculated values might appear due to the non-perfect suppression of reflections in the connectors.

To estimate the accuracy of the perturbation localization with the proposed method, we introduced strong excess bend losses that decreased the fiber transmission by more than 30 dB at the first and the last 100 m of the fiber. Fig. 3(a) shows the measured relationship between the location of the strong perturbation and the normalized Rayleigh backscattered power for the first 100 m of the sensing fiber. Whereas backscattered power depends on the perturbation position, the normalized transmitted power remained practically constant. The maximum deviation of the experimental points from its linear fit does not exceed 1 m, and the standard deviation of the linear fit is less than 0.75 m. Fig. 3(b) presents the relationship between the location of a strong perturbation and the normalized Rayleigh backscattered power for the last 100 m of the sensing fiber. Maximum deviation here does not exceed 5 m, and the standard deviation is less than 2.5 m. Taking into account that linear fits of the experimental data practically coincide with the numerical prediction, we conclude that with the proposed method, we can localize a strong perturbation with an error less than 1 m for the first 100 m, and less than 5 m for the last 100 m of a 4.04 km long sensing fiber.

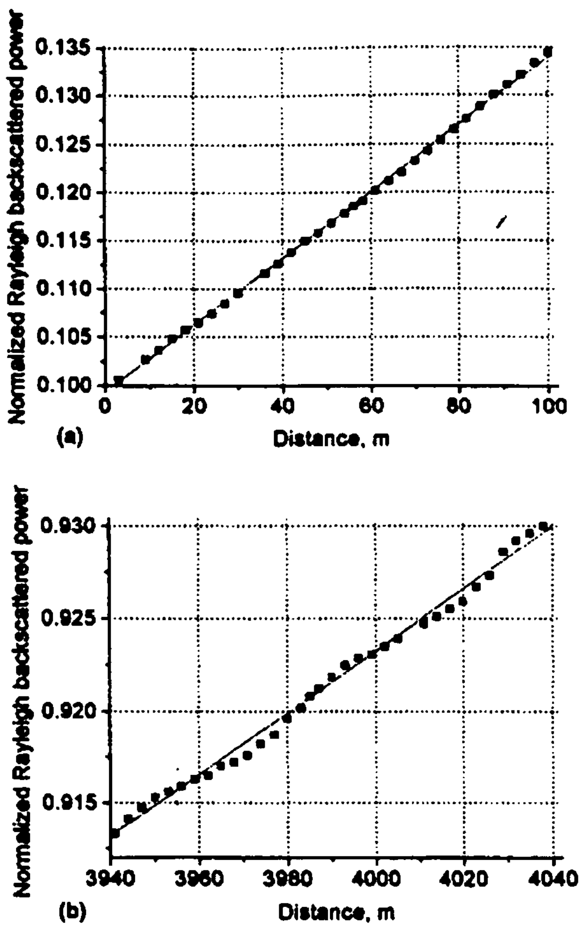

Fig. 3. Normalized Rayleigh backscattered power on location of strong excess loss (points) and its linear fit (solid line) for the perturbation applied to: (a) the first, and (b) the last 100 m of the test fiber.

There are a few features that are inherent in the proposed method. First of all, it follows from the data presented in Fig. 2 that it is easier to localize strong perturbations with the proposed method,

but the localization of weak perturbations requires higher accuracy of the measurement of transmitted and Rayleigh backscattered powers. Secondly, the slope of the linear fit for the last 100 m of the sensing fiber exceeds the slope for the first 100 m (see Fig. 3(a) and (b)). This means that for the localization of the perturbation at the end of the test fiber, we need to measure the Rayleigh backscattered power with higher accuracy than for a perturbation close to the source-end of the fiber. The third feature is that the noise level increases with the distance along the sensing fiber (see Fig. 3(a) and (b)). However, this effect can be suppressed if we repeat the measurements from the other end of the sensing fiber. Furthermore, the symmetrical configuration also allows for the localization of two strong disturbances simultaneously. Note that, in general, using this algorithm, we can localize only a single strong or weak perturbation, which may appear along the sensing fiber.

4. Conclusion

In conclusion, we have demonstrated that the proposed alarm-condition sensor based on Rayleigh scattering allows the localization of one loss-inducing perturbation along a sensing fiber by measuring only the transmitted and Rayleigh backscattered powers of unmodulated CW light. Localization of a strong disturbance with an accuracy of 1 m close to the source-end and 5 m close to the output-end of the 4.04 km long single-mode sensing fiber was demonstrated. We believe the proposed technique should be very attractive for the eventual realization of a compact and inexpensive distributed alarm fiber-optic sensor.

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